Global polarization and spin alignment measurements in heavy-ion collisions at RHIC and LHC

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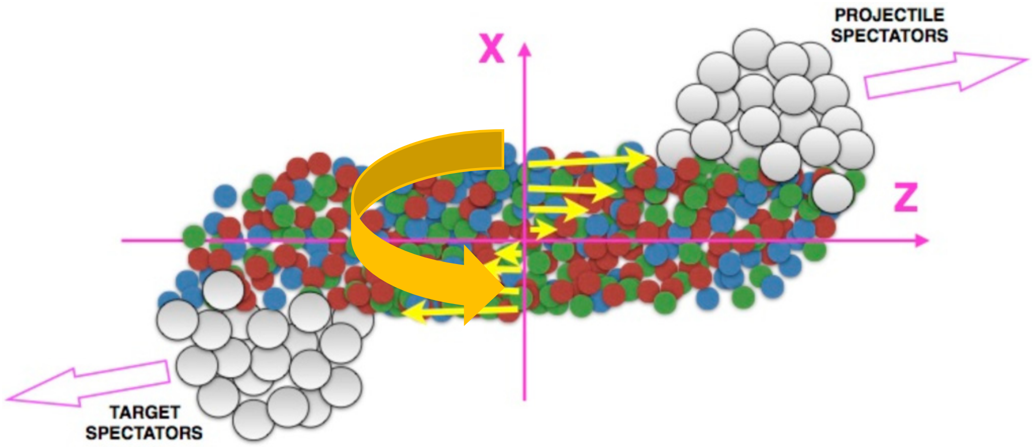
NICA-MPD Collaboration Meeting, 2024/10/14-16

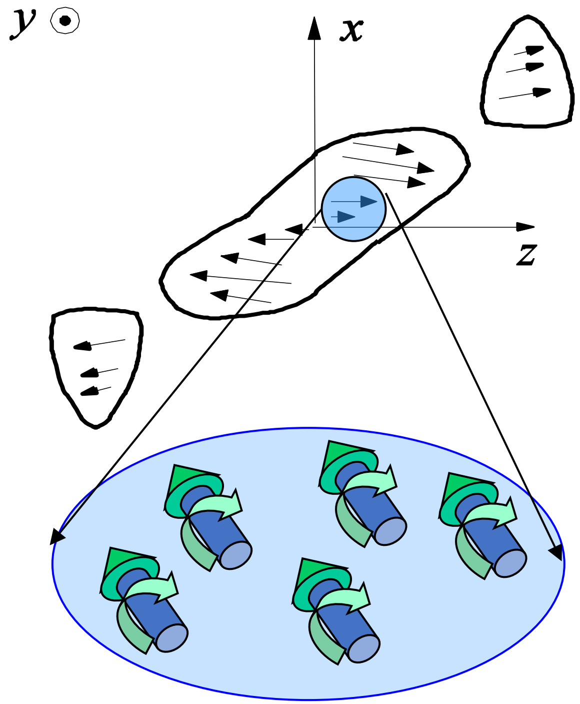
Outline

- Brief introduction of the global polarization
- Measurements in heavy-ion collisions and prospects
    - Hyperon polarization
    - Vector meson spin alignment
- Summary

Global polarization in HIC

Liang, Wang Phys. Rev. Lett. **94**, 102301(2005); Phys. Lett. B **629**, 20 (2005)



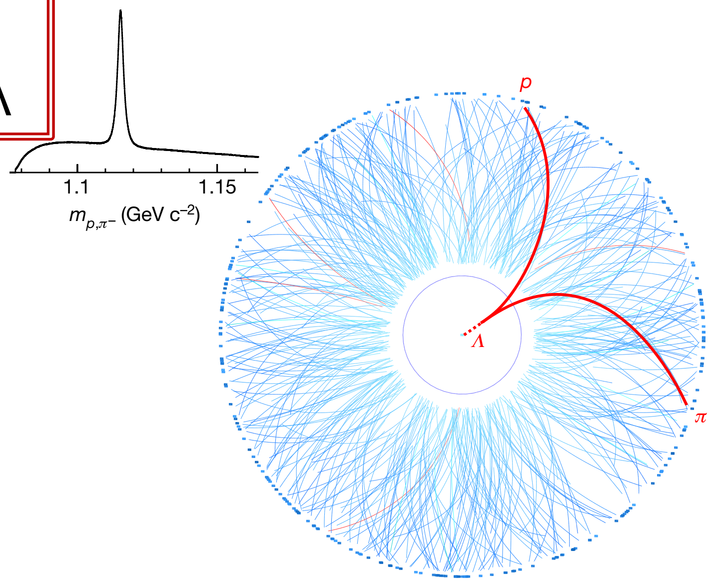


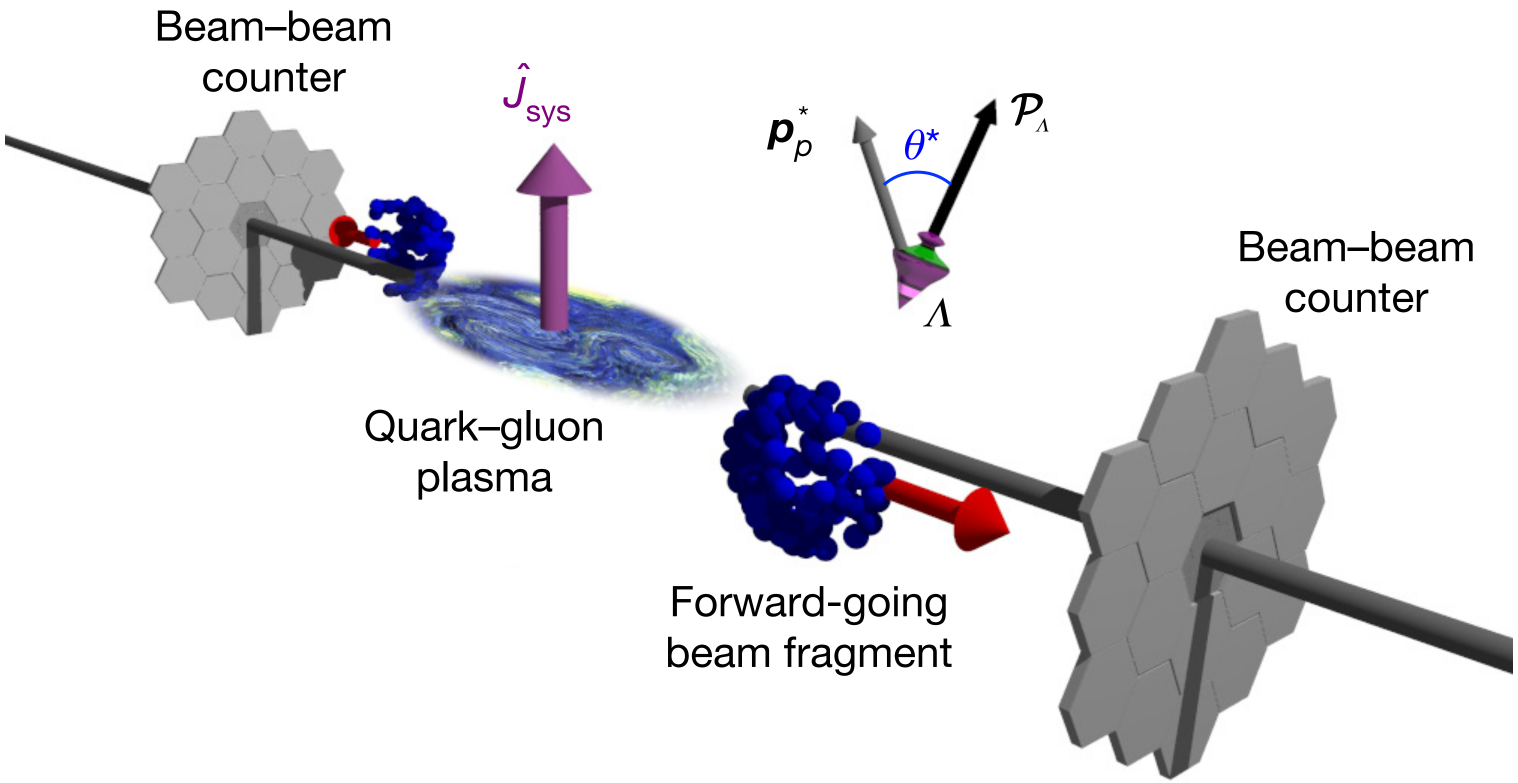
Large OAM *L* is deposited in the interaction region

- The initial momentum gradient should result in a net angular momentum (shear) in this direction that will be transferred to quark spin via spin-orbit interaction, this effect may not be washed out during interaction and hadronization
- Spin-vorticity coupling Betz, Gyulassy, Torrieri Phys. Rev. C **76**, 044901 (2007); Becattini, Piccinini, Rizzo Phys. Rev. C **77**, 024906 (2008)
- Connection to classical world, the Barnett effect, a fraction of the *L* associated with the body rotation is transformed into the spin *L* of the electron

Experimental measurements: Λ

- The global quark polarization along L have many observable consequences in non-central HIC
- Λ are self-analyzing, proton tends to be emitted along the spin direction of the Λ



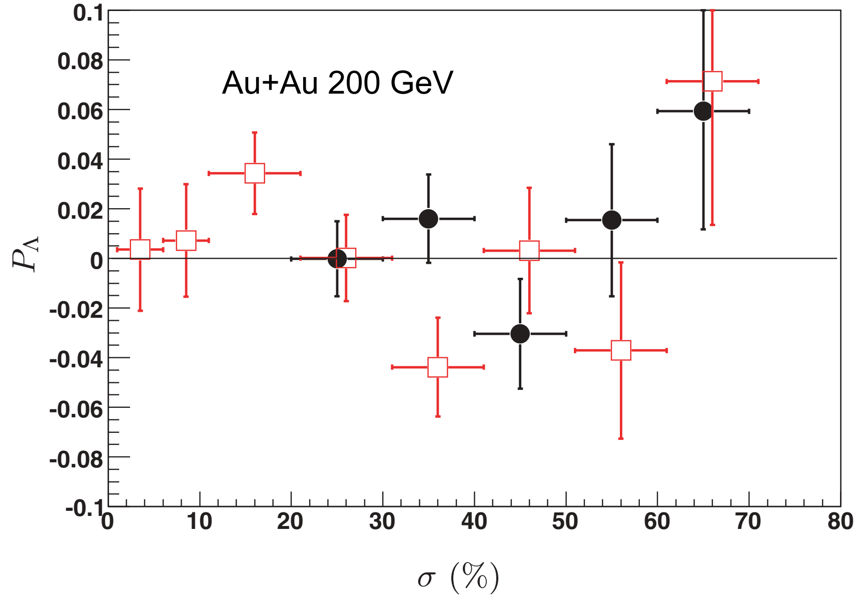


$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1+\alpha_{\mathrm{H}}|\mathcal{P}_{\mathrm{H}}|\cos\theta^*)$$

$$P_H = \frac{8}{\pi\alpha_H}\frac{\langle\sin(\Psi_1^{\mathrm{obs}}-\phi_p^*)\rangle}{\mathrm{Res}(\Psi_1)}$$

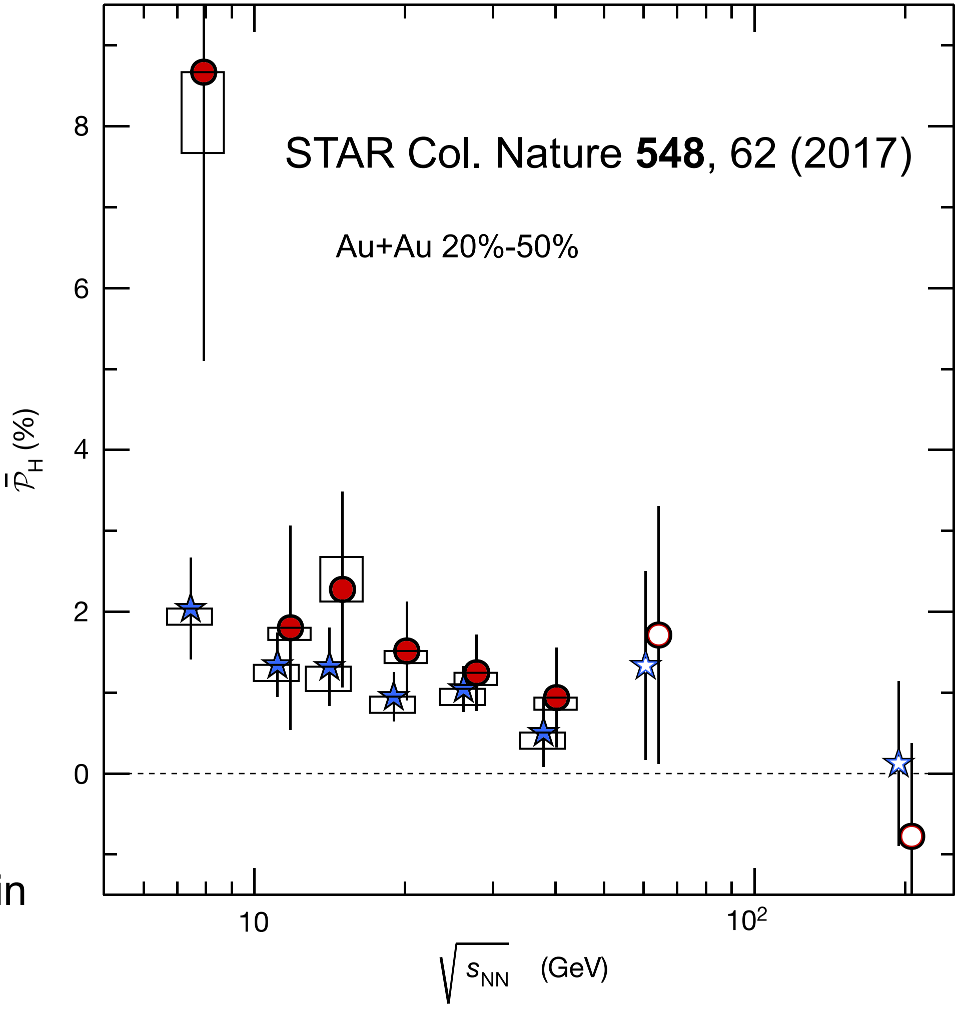
Experimental measurements: Λ (cont.)

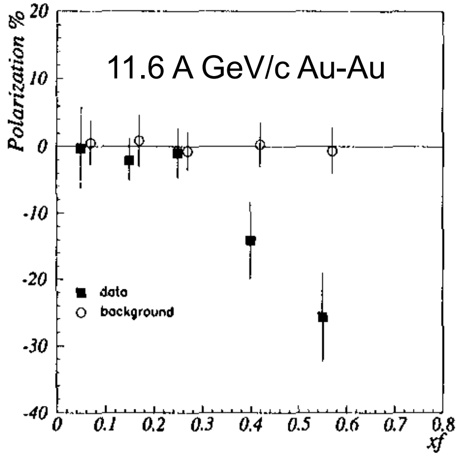
STAR Col. Phys. Rev. C **76**, 024915 (2007)



from 2007 to 2017

Lambda hyperons show a positive polarization of the order of a few percent





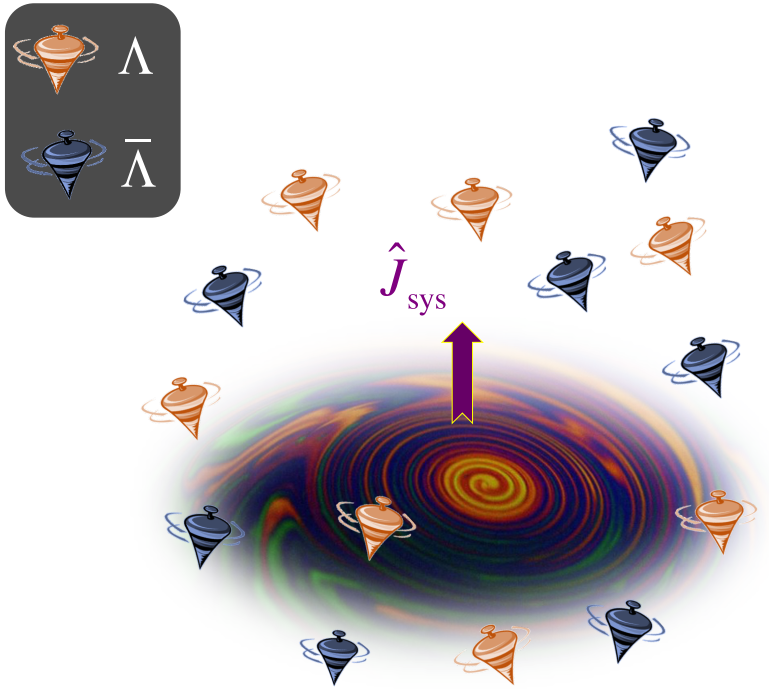
R. Bellwied for E896 Col.
QM2001, Nucl. Phys. A 698, 499 (2002)

"The produced Λ are polarized at freeze-out in the heaviest collision system"

…

"The STAR detector will be capable of repeating these measurements at RHIC energies"

Experimental measurements: Λ (cont.2)



- The fluid vorticity was estimated from the data using hydrodynamics relation

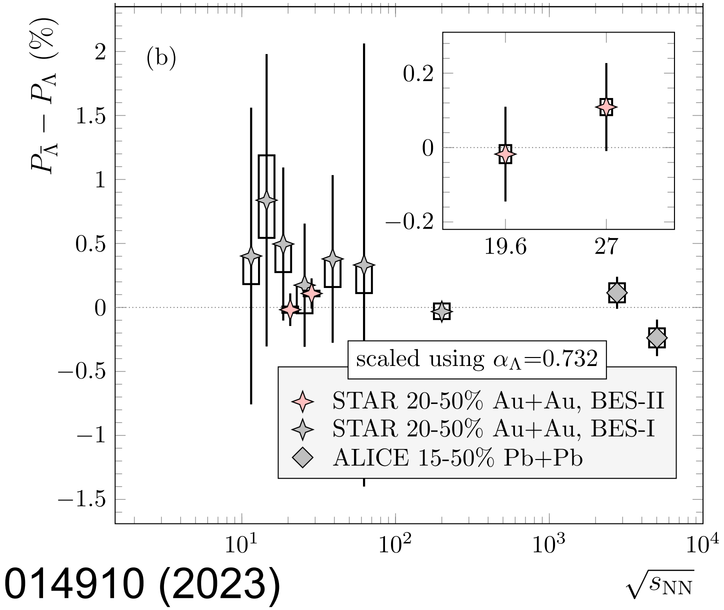
$$\omega \approx k_B T(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\bar{\Lambda}'})/\hbar$$

- The collision energy-average polarization data from STAR BES-I indicate a vorticity of **(9±1)x10^{21} s^{-1}**

  →experimental access to the vortical structure of the QGP

- Late-stage B field

$$|B| \approx \frac{T_s|P_{\bar{\Lambda}} - P_{\Lambda}|}{2|\mu_{\Lambda}|}$$

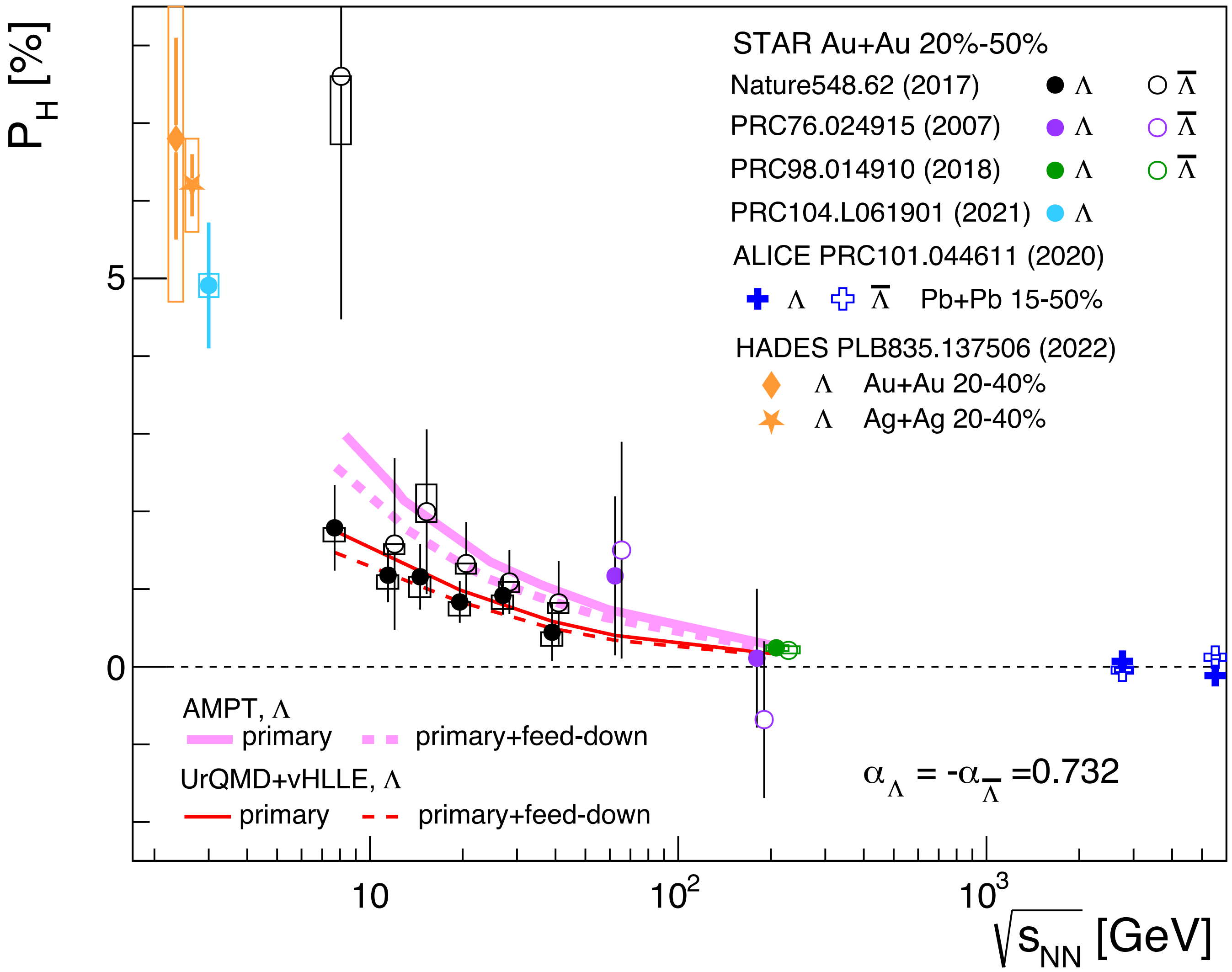


STAR Col. Phys. Rev. C **108**, 014910 (2023)

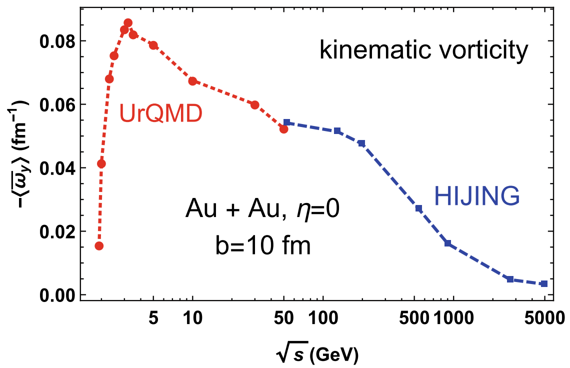
- High precision BES-II data of 19.6 and 27 GeV
  - -0.018 ± 0.127 (stat.) ± 0.024 (syst.)
  - 0.109 ± 0.118 (stat.) ± 0.022 (syst.)

$B < 9.4 \times 10^{12}$ T and $B < 1.4 \times 10^{13}$ T

Measurements of Λ and Ξ,Ω



- Measurements in different Exps.
  -didn't see the "drop" trend?



Deng et al., Phys. Rev. C **101**, 064908 (2020)
Guo et al., Phys. Rev. C **104**, L041902 (2021)…

- Measurements extend to multistrange

STAR Col. Phys. Rev. Lett. **126**, 162301 (2021)

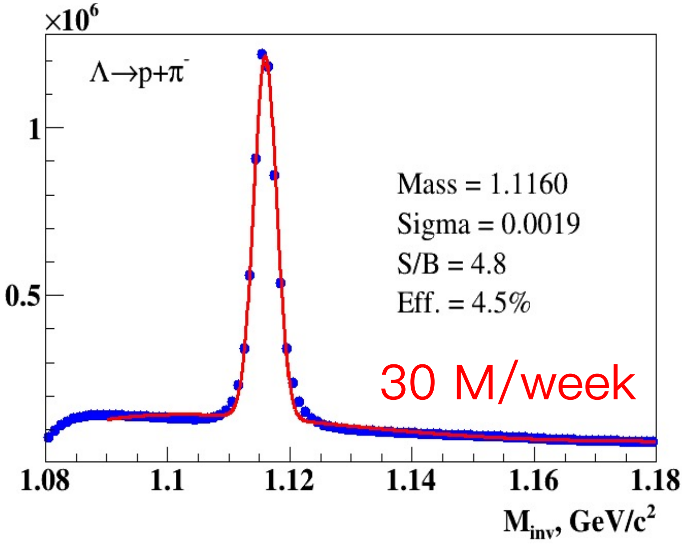
$$\langle P_\Xi \rangle = 0.47 \pm 0.10(\text{stat}) \pm 0.23(\text{syst})\%$$

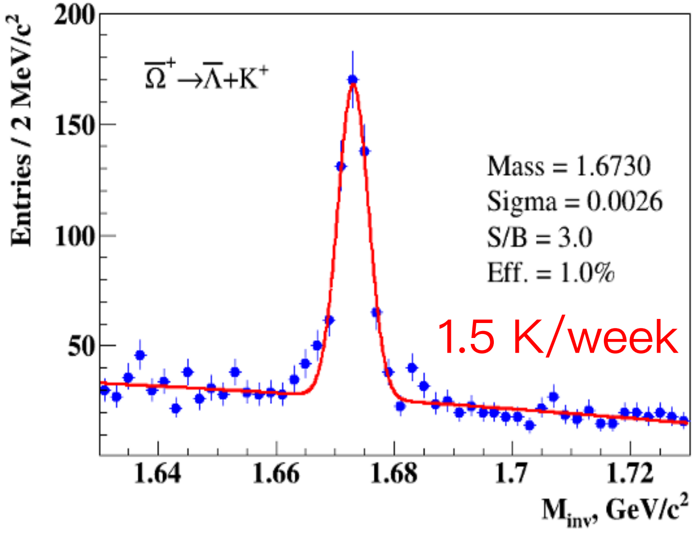
$$\langle P_\Omega \rangle = 1.11 \pm 0.87(\text{stat}) \pm 1.97(\text{syst})\%$$

Prospects at NICA-MPD

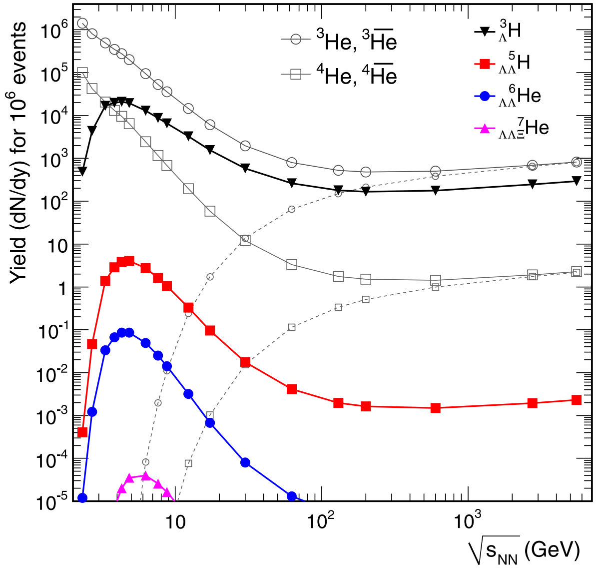
Heavy ion colliding beams: upto Au @ $\sqrt{s_{NN}}$ = 4 – 11 GeV ➔ **MPD**

- The energies are exactly located at the place to understand the transitions?





Figs. from Zebo

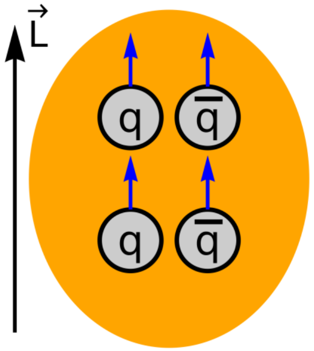


Andronic et al., Phys. Letts. B **697** (2011) 203

- The detectors are powerful to identify hyperons with good signal to background ratio, and maybe the light hypernuclei polarization feasible?

Experimental measurements: φ,K*

- Vector meson ($J=1^-$) spin alignment

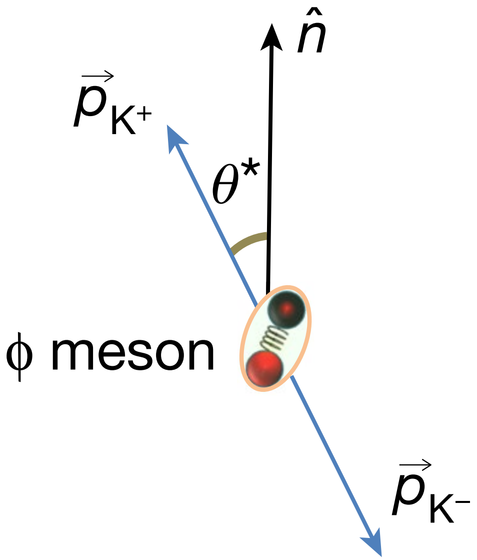


- ✓ Spin tensor polarization
- ✓ Different probabilities among three spin states
- ✓ Only ρ_{00} is measurable

$$|11\rangle = |\uparrow\uparrow\rangle$$

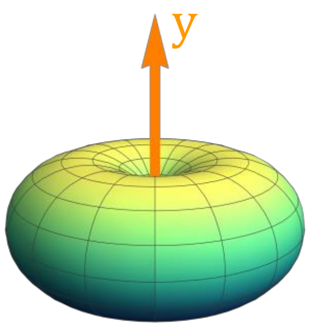
$$|10\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

$$|1\text{-}1\rangle = |\downarrow\downarrow\rangle$$

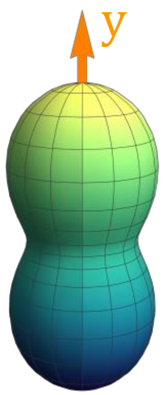


$$\rho^V = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$

$$\frac{dN}{d(\cos\theta^*)} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$



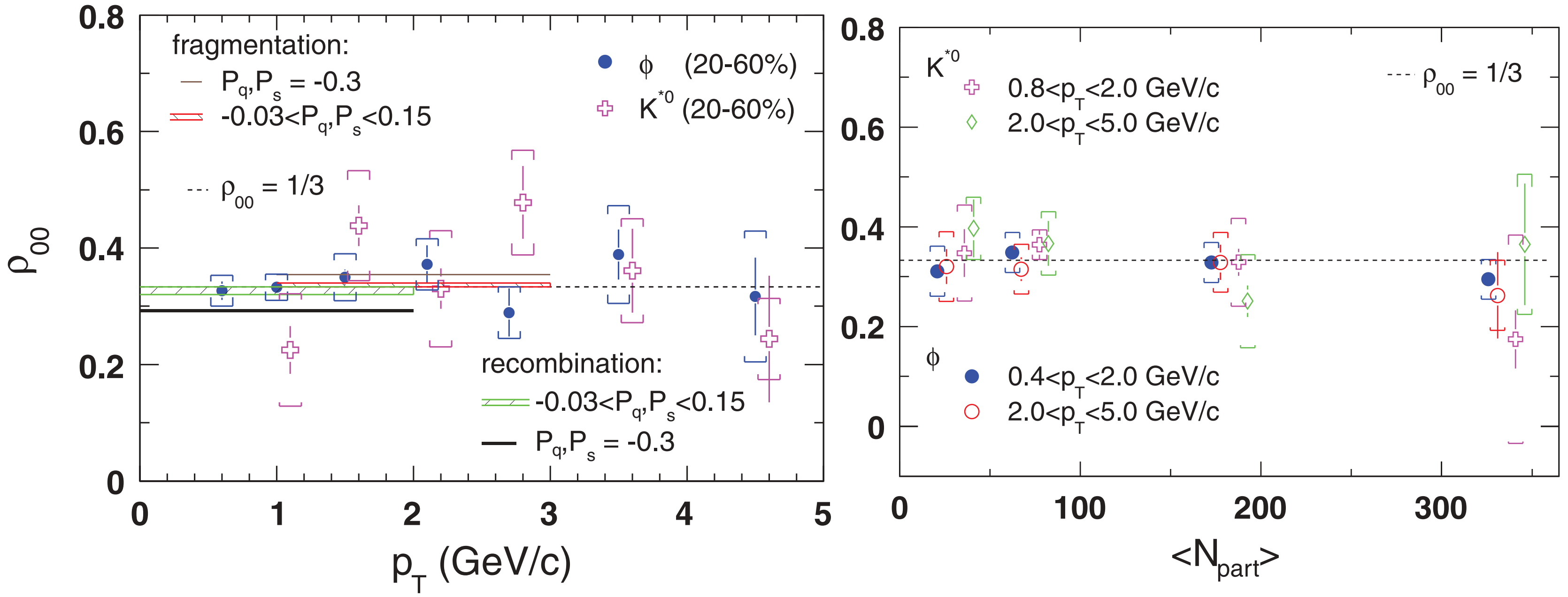
$\rho_{00} < 1/3$

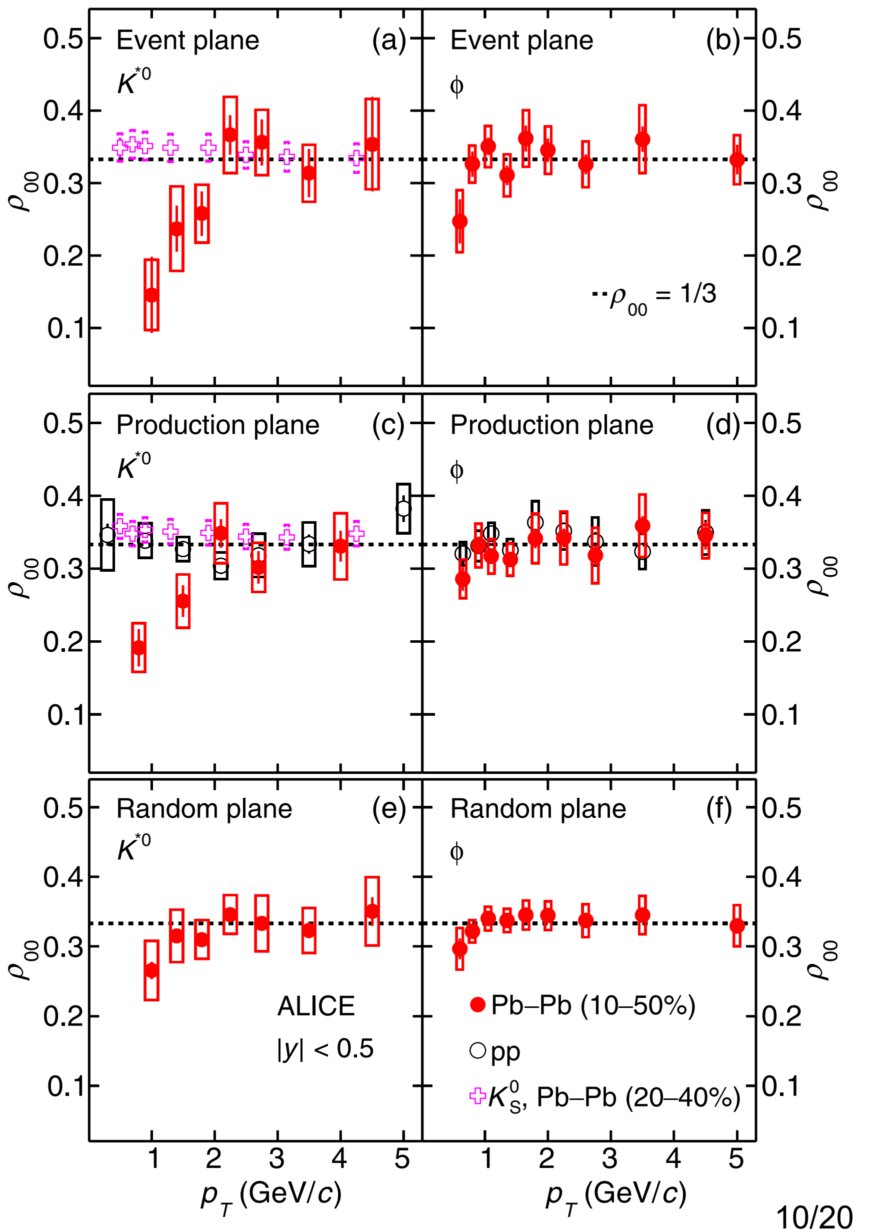


$\rho_{00} > 1/3$

Experimental measurements: φ,K*(cont.)

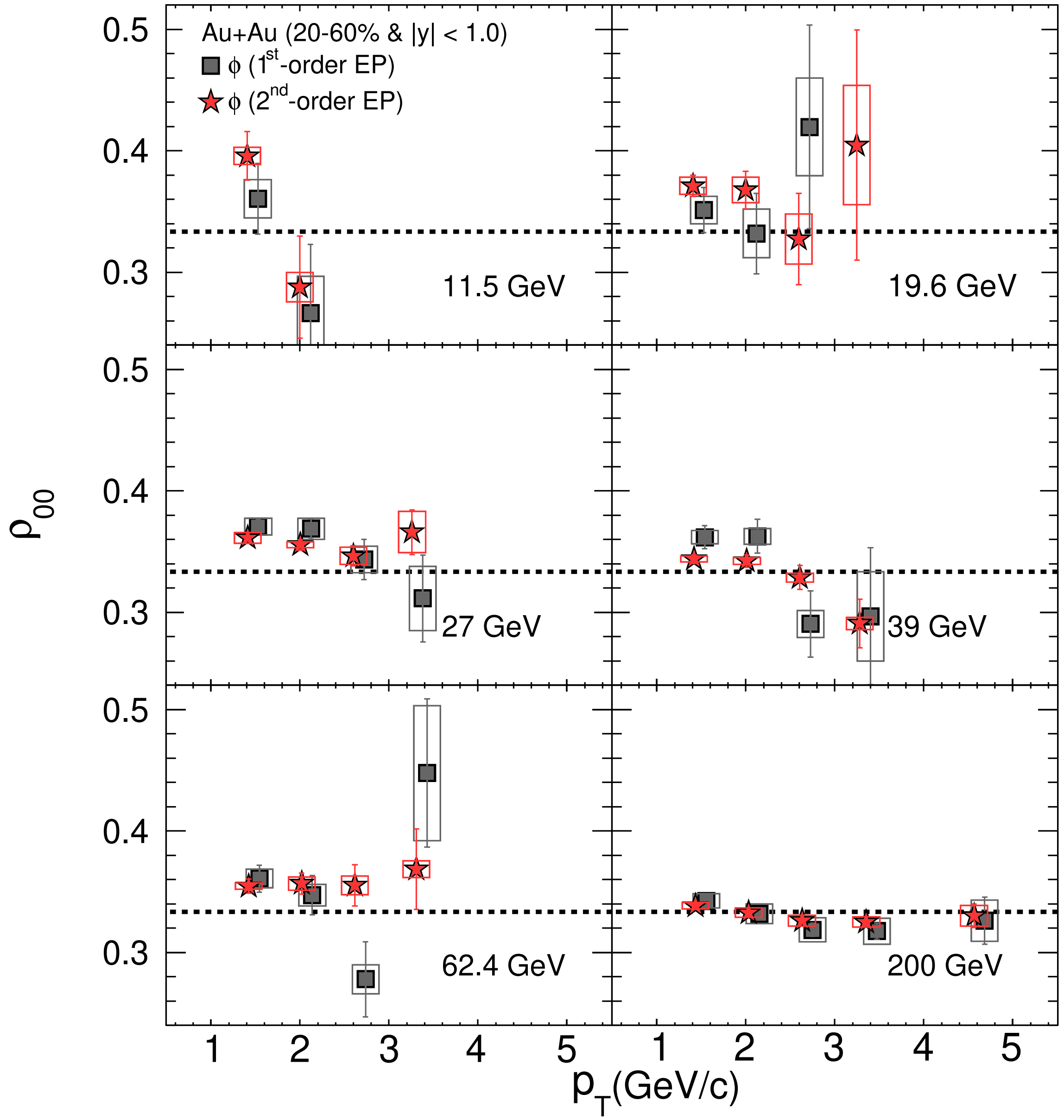
STAR Col. Phys. Rev. C **77**, 061902® (2008)   ALICE Col. Phys. Rev. Lett. **125**, 012301 (2020)





- Early data of Au+Au 200 GeV suffer from large uncertainties
- Updated measurements seem to provide evidence of spin-orbital angular momentum interactions, but production plane and random plane also show deviation at small p_T

New Measurements φ,K^{*0}@non-central collisions

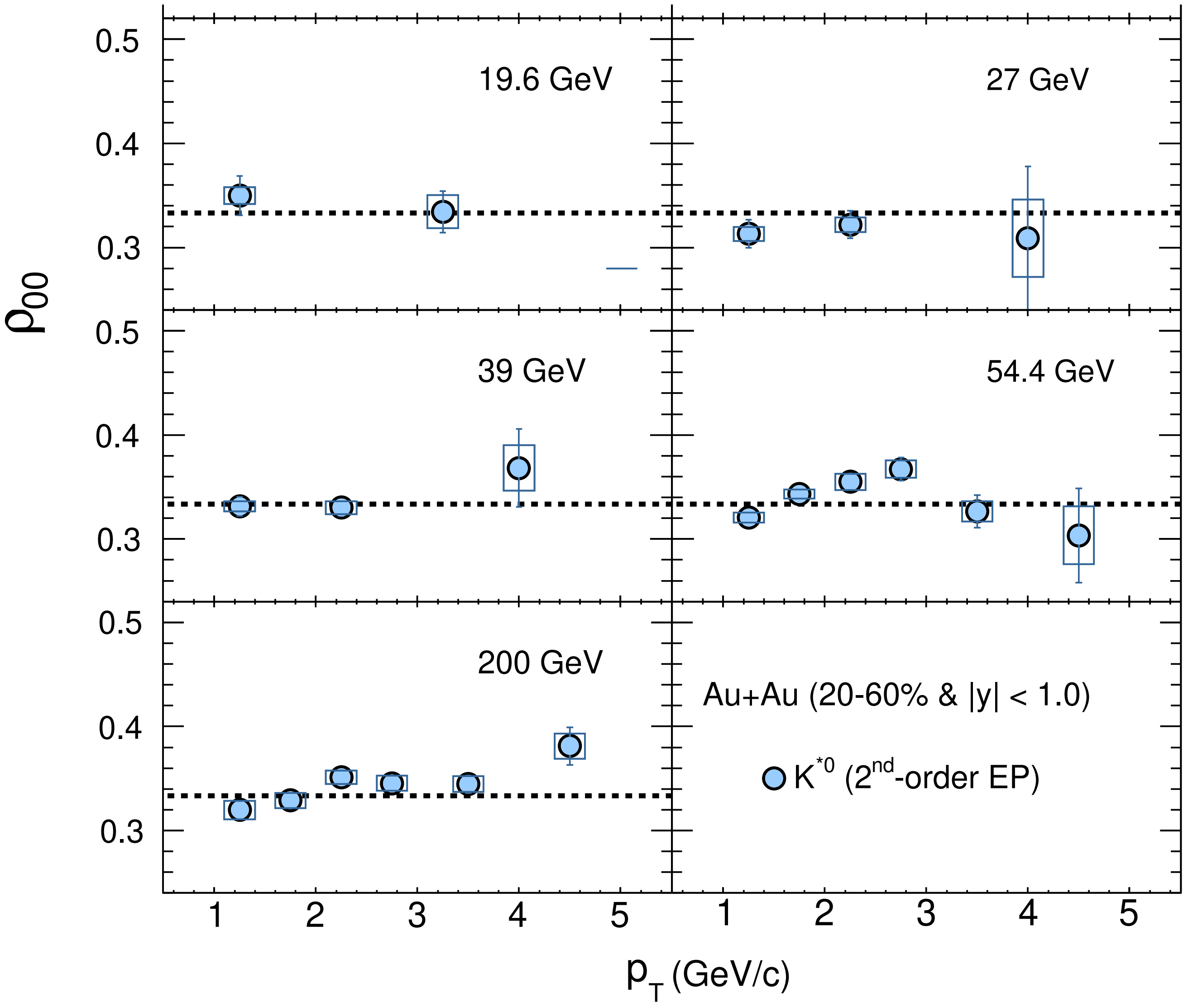


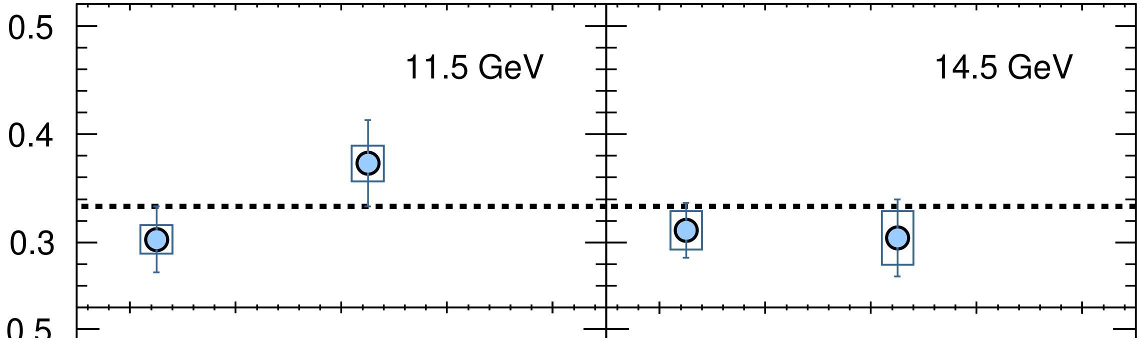
- New measurements extend the study to lower energies with high statistics, @200 GeV, a factor of ~50 more event statistics analyzed.
- We see that the signal for the φ meson occurs mainly within ~1.0-2.4 GeV/c; at larger p_T the results can be regarded as being consistent with 1/3 within ~2σ or less.

* 1st order EP: ZDC or BBC
* 2nd order EP: TPC

STAR Col. Nature **614**, 244 (2023)

New Measurements φ,K*⁰@non-central collisions



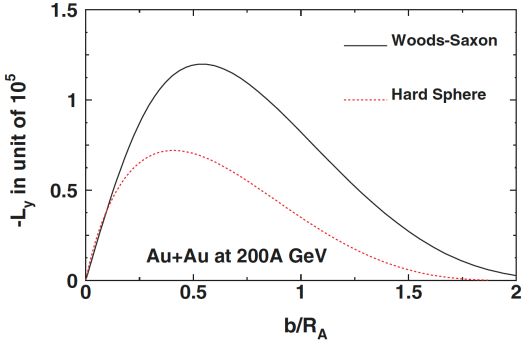


- K^{*0} is a combination of K^{*0} and anti-K^{*0}
- Independent analysis
- Different from the φ meson data, the K^{*0} data is largely consistent with 1/3, within statistics and systematical uncertainties

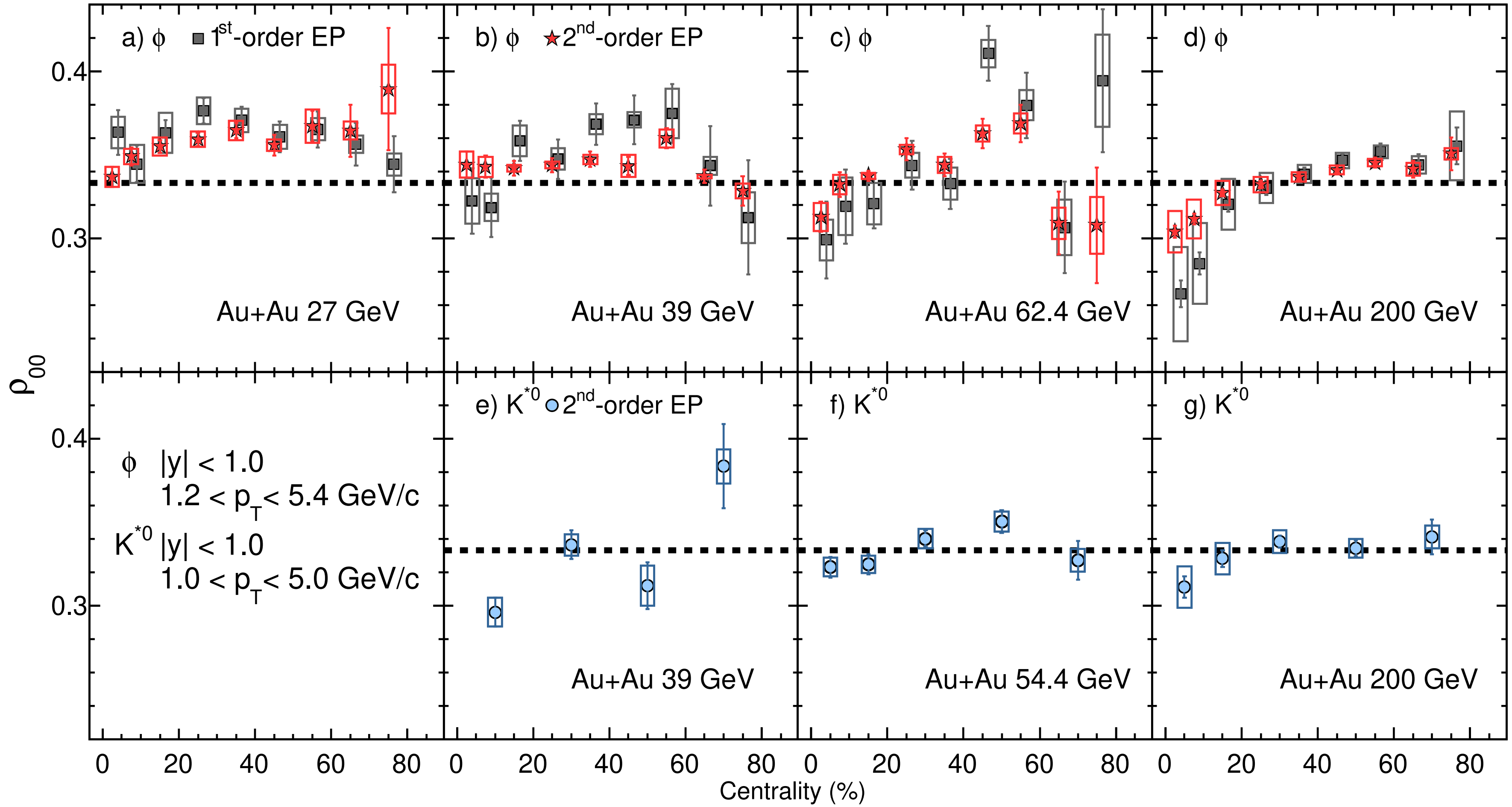
STAR Col. Nature **614**, 244 (2023)

Study the fine structure vs. centrality

STAR Col. Nature **614**, 244 (2023)

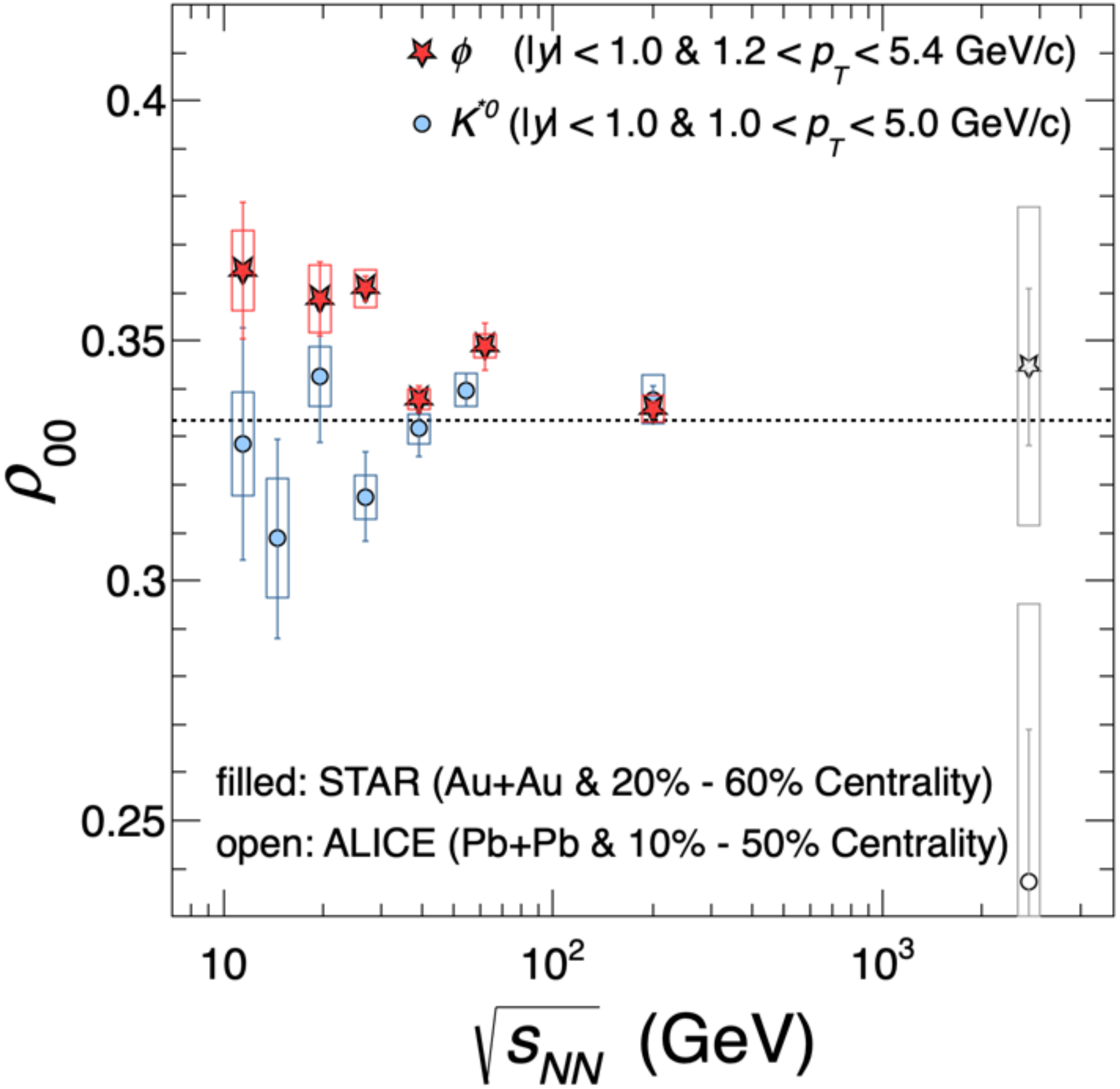


Gao, Chen, Deng, Liang, Wang, Wang
Phys. Rev. C **76**, 044901 (2007)



At high energies (≥62.4 GeV) for φ, and (≥39 GeV) for K^{*0}, ρ_{00} in central collisions tends to ≤1/3. This might be caused by transerve local spin alignment and a contribution from the helicity polarization of quarks.

Results mid-central & averaged over p_T



1) φ-meson is significantly above 1/3 for sqrt{s}≤ 62 GeV

2) K* is largely consistent with 1/3

3) Averaged over 62 GeV and below:

- 0.3541 ± 0.0017 (stat.) ± 0.0018 (sys.) for φ
- 0.3356 ± 0.0034 (stat.) ± 0.0043 (sys.) for K*

* Different approaches are used in the combinatorial bg. analysis

STAR Col. Nature **614**, 244 (2023)

Expectations of ρ_{00} from theory

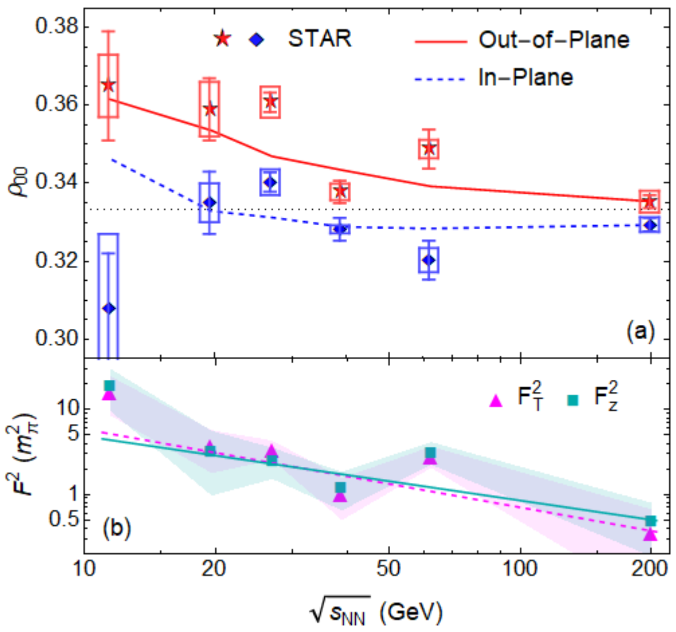
Physics Mechanisms	(ρ_{00})
c_Λ: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
c_ε: Vorticity tensor[1]	< 1/3 (Negative ~ 10^{-4})
c_E: Electric field[2]	> 1/3 (Positive ~ 10^{-5})
Fragmentation[3]	> or, < 1/3 (~ 10^{-5})
Local spin alignment and helicity[4]	< 1/3
Turbulent color field[5]	< 1/3
c_ϕ: Vector meson strong force field[6]	> 1/3

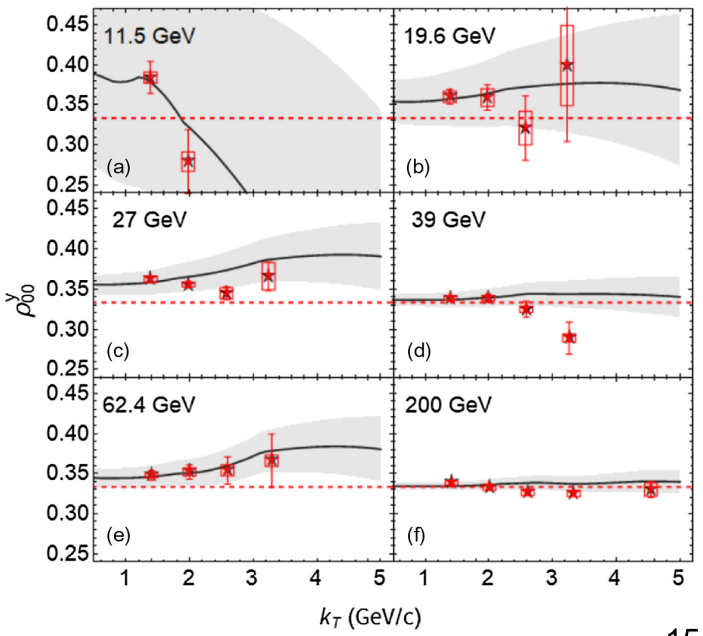
$$\rho_{00}^{\phi} \approx \frac{1}{3} + c_\omega + c_\varepsilon + c_{\mathrm{EM}} + c_\phi + c_{\mathrm{LV}} + c_h + c_{\mathrm{TC}} + c_{\mathrm{shear}}$$

[1]. Yang et al., Phys. Rev. C **97**, 034917 (2018) [2]. Sheng et al., Phys. Rev. D **101**, 096005 (2020)
[3]. Xia et al., Phys. Lett. B **817**, 136325 (2021) [4]. Gao, Phys. Rev. D **104**, 076016 (2021)
[5]. Muller, Yang, Phys. Rev. D **105**, L011901 (2022) [6]. Li, Liu, arXiv:2206.11890, Wagner, Weickgenannt, Speranza, arXiv:2207.01111

The local correlation or fluctuation of φ fields is the dominant mechanism for the observed φ-meson ρ_{00}

Sheng, et al., Phys. Rev. Lett. **131**, 042304 (2023)





The small Λ vs. large φ-meson signal

Lv, Yu, Liang, Wang, Wang, PRD **109**, 114003 (2024)

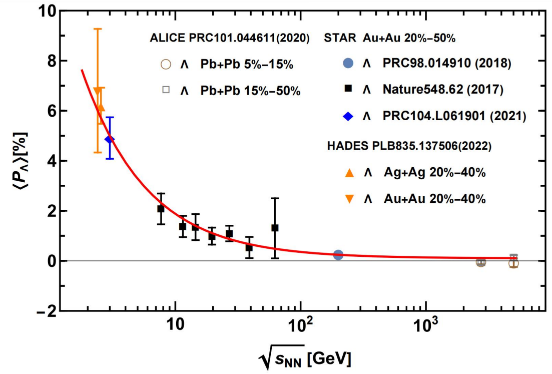
$$\rho_{00}^{V} = \frac{1}{C_V}\left\{1 + c_{xx}^{(q_1\bar{q}_2)} + c_{yy}^{(q_1\bar{q}_2)} - c_{zz}^{(q_1\bar{q}_2)} + P_{q_1x}P_{\bar{q}_2x} + P_{q_1y}P_{\bar{q}_2y} - P_{q_1z}P_{\bar{q}_2z}\right\}$$

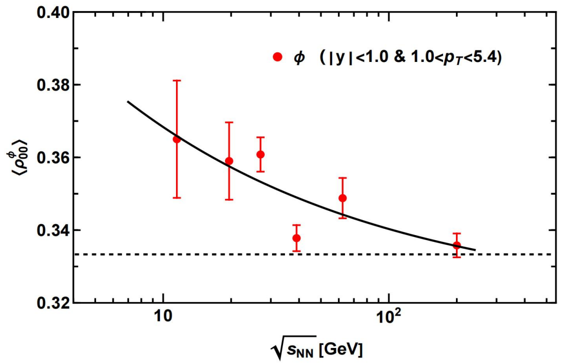
$$P_\Lambda(\alpha_\Lambda) = \bar{P}_{sz} - \frac{\bar{c}_{iiz}^{(uds)} + \bar{c}_{iz}^{(us)}\bar{P}_{di} + \bar{c}_{iz}^{(ds)}\bar{P}_{ui}}{1 - \bar{c}_{ii}^{(ud)} - \bar{P}_{ui}\bar{P}_{di}}$$

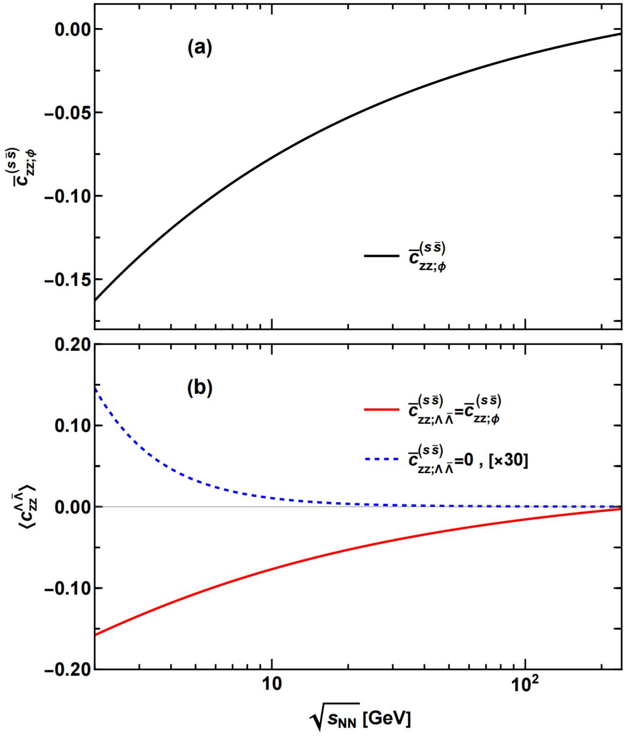
$$\langle P_\Lambda \rangle \sim \langle P_s \rangle,$$

$$\langle \rho_{00}^{\phi} \rangle \sim \frac{1 - \bar{c}_{zz;\phi}^{(s\bar{s})} - \langle P_s \rangle^2}{3 + \bar{c}_{zz;\phi}^{(s\bar{s})} + \langle P_s \rangle^2},$$

$$\langle c_{zz}^{\Lambda\bar{\Lambda}} \rangle \sim \bar{c}_{zz;\Lambda\bar{\Lambda}}^{(s\bar{s})} + \langle P_s \rangle^2,$$



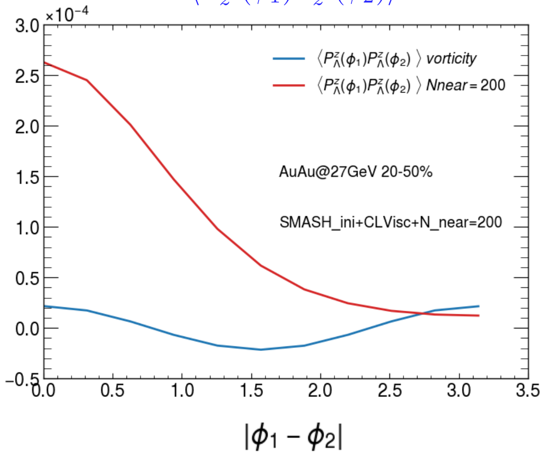




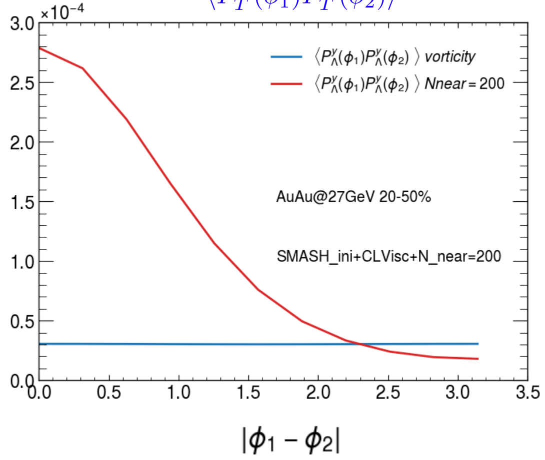
X.N. Wang, Chirality 2024 7/22-26, Romania

"Strong-field induced hyperon spin correlation"

$\langle P_z^\Lambda(\phi_1) P_z^\Lambda(\phi_2) \rangle$



$\langle P_T^\Lambda(\phi_1) P_T^\Lambda(\phi_2) \rangle$



*quark-antiquark spin correlations in ee/pp (helicity frame)

Chen, Goldstein, Jaffe, Ji, NPB **445**, 380 (1995); Chen, Yang, Zhou, Liang, PRD **95**, 034009 (2017); Zhang, Wei, PLB **839**, 137821 (2023)

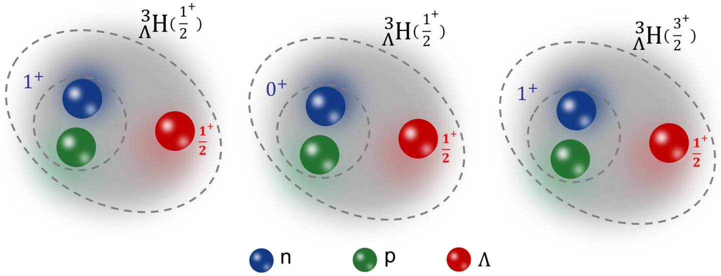
The spin-spin correlations

- Spin-spin correlations and hypernuclei polarization in HIC

Shen, Chen, Tang, arXiv:2407.21291

$$c'_{\Lambda\Lambda} = \frac{64}{\pi^2\alpha_\Lambda^2}\frac{\langle \sin(\phi_i^* - \Psi_{\rm EP})\sin(\phi_j^* - \Psi_{\rm EP})\rangle}{\langle \cos^2(\Psi_{\rm EP} - \Psi_{\rm RP})\rangle} - P_\Lambda^2,$$

$$B(c'_{OS}, c'_{SS}) = \frac{1}{2}\left(\frac{c'_{\Lambda\bar{\Lambda}} - c'_{\Lambda\Lambda}}{c'_{\Lambda\bar{\Lambda}} + c'_{\Lambda\Lambda}} + \frac{c'_{\bar{\Lambda}\Lambda} - c'_{\bar{\Lambda}\bar{\Lambda}}}{c'_{\bar{\Lambda}\Lambda} + c'_{\bar{\Lambda}\bar{\Lambda}}}\right).$$



Sun, Liu, Zhen, Chen, Ko, Ma, arXiv:2405.12015

J^P	structure	decay mode	$\frac{dN}{d\cos\theta^*}$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(1^+)$	${}^3_\Lambda\mathrm{H} \to \pi^- + {}^3\mathrm{He}$	$\frac{1}{2}(1 - \frac{1}{2.58}\alpha_\Lambda \mathcal{P}_\Lambda \cos\theta^*)$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(0^+)$	${}^3_\Lambda\mathrm{H} \to \pi^- + {}^3\mathrm{He}$	$\frac{1}{2}(1 + \alpha_\Lambda \mathcal{P}_\Lambda \cos\theta^*)$
$\frac{3}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(1^+)$	${}^3_\Lambda\mathrm{H} \to \pi^- + {}^3\mathrm{He}$	$\frac{1}{2}\left(1 - \mathcal{P}_\Lambda^2(3\cos^2\theta^* - 1)\right)$
$\frac{1}{2}^-$	$\bar{\Lambda}(\frac{1}{2}^-) - \overline{np}(1^-)$	${}^3_{\bar{\Lambda}}\overline{\mathrm{H}} \to \pi^+ + {}^3\overline{\mathrm{He}}$	$\frac{1}{2}(1 - \frac{1}{2.58}\alpha_{\bar{\Lambda}} \mathcal{P}_{\bar{\Lambda}} \cos\theta^*)$
$\frac{1}{2}^-$	$\bar{\Lambda}(\frac{1}{2}^-) - \overline{np}(0^-)$	${}^3_{\bar{\Lambda}}\overline{\mathrm{H}} \to \pi^+ + {}^3\overline{\mathrm{He}}$	$\frac{1}{2}(1 + \alpha_{\bar{\Lambda}} \mathcal{P}_{\bar{\Lambda}} \cos\theta^*)$
$\frac{3}{2}^-$	$\bar{\Lambda}(\frac{1}{2}^-) - \overline{np}(1^-)$	${}^3_{\bar{\Lambda}}\overline{\mathrm{H}} \to \pi^+ + {}^3\overline{\mathrm{He}}$	$\frac{1}{2}\left(1 - \mathcal{P}_{\bar{\Lambda}}^2(3\cos^2\theta^* - 1)\right)$

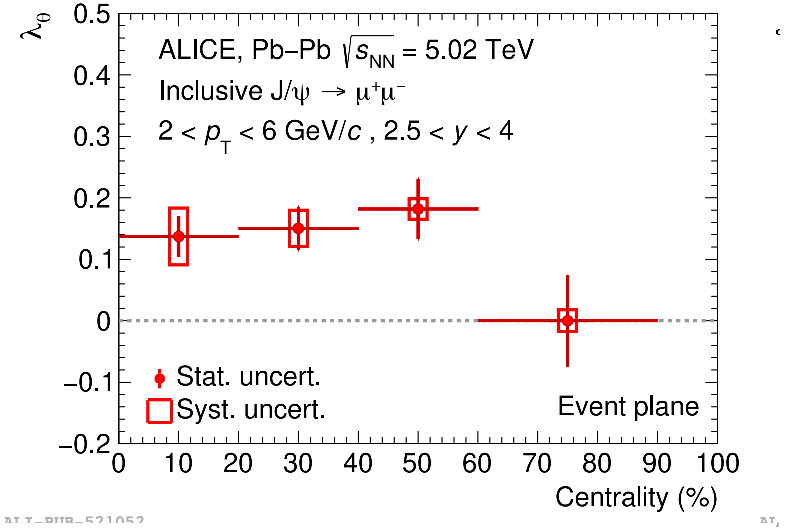
$$\mathcal{P}_{{}^3_\Lambda\mathrm{H}} \approx \frac{\frac{2}{3}\langle\mathcal{P}_n\rangle + \frac{2}{3}\langle\mathcal{P}_p\rangle - \frac{1}{3}\langle\mathcal{P}_\Lambda\rangle - \langle\mathcal{P}_n\mathcal{P}_p\mathcal{P}_\Lambda\rangle + C_-}{1 - \frac{2}{3}(\langle(\mathcal{P}_n + \mathcal{P}_p)\mathcal{P}_\Lambda\rangle) + \frac{1}{3}\langle\mathcal{P}_n\mathcal{P}_p\rangle + C_+} \quad (15)$$

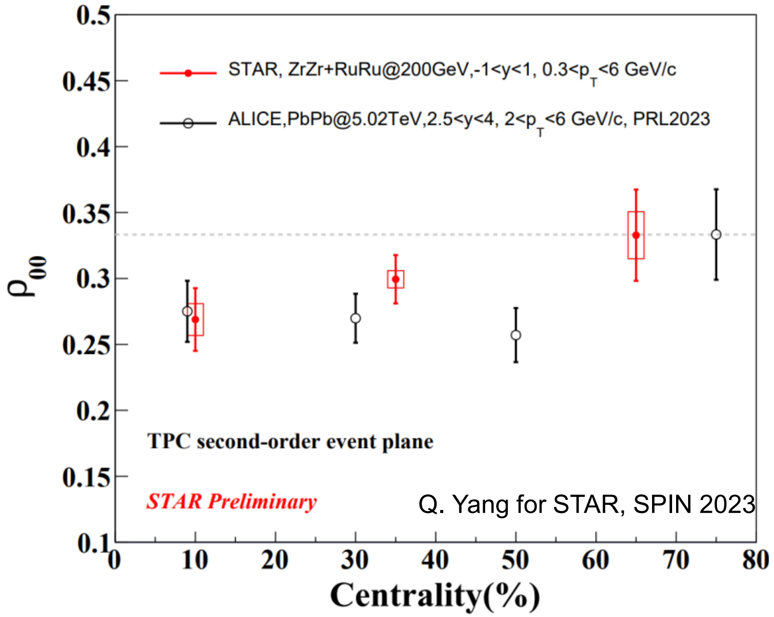
$$C_- = -\frac{1}{4}(\langle c^{zz}_{np}\mathcal{P}_\Lambda\rangle + \langle c^{zz}_{p\Lambda}\mathcal{P}_n\rangle + \langle c^{zz}_{n\Lambda}\mathcal{P}_p\rangle) - \frac{1}{4}\langle c^{zzz}_{np\Lambda}\rangle,$$

$$C_+ = \frac{1}{12}(\langle c^{zz}_{np}\rangle - 2\langle c^{zz}_{p\Lambda}\rangle - 2\langle c^{zz}_{n\Lambda}\rangle). \quad (16)$$

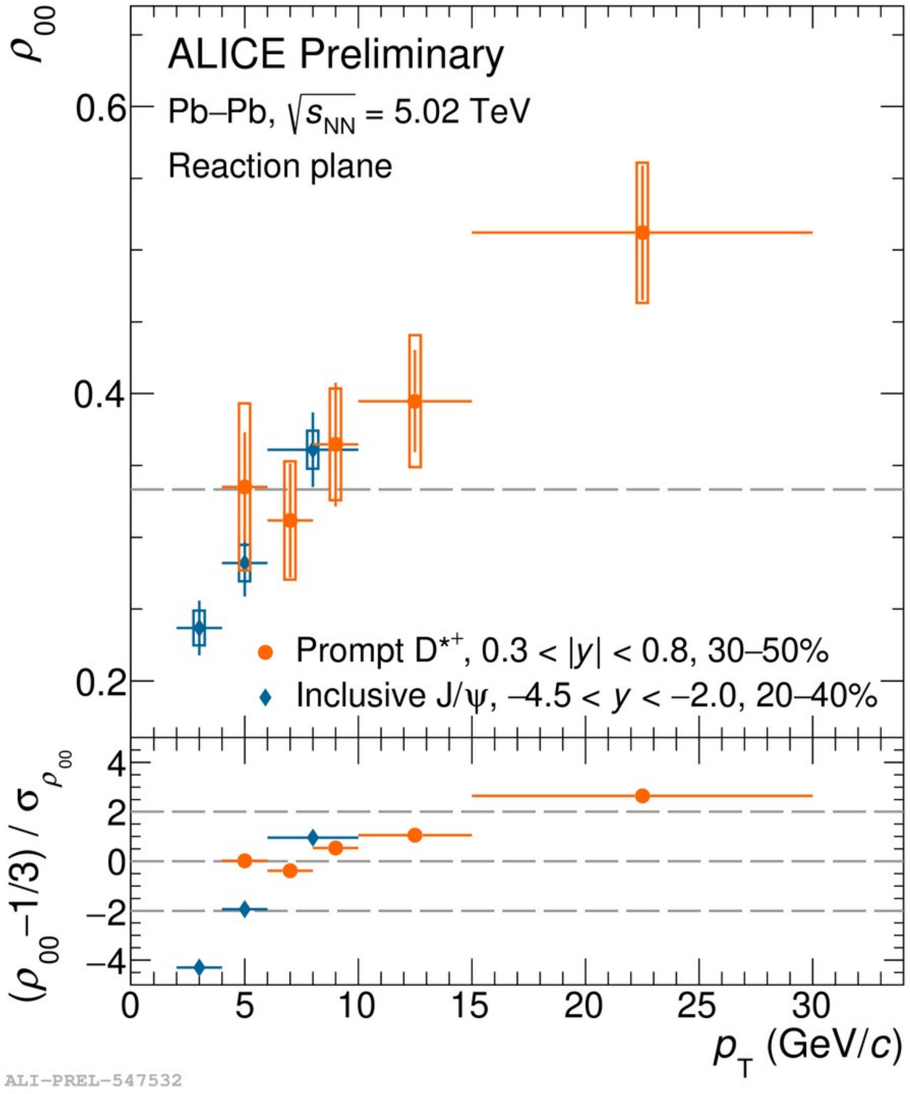
From φ to other mesons

ALICE Col. Phys. Rev. Lett. **131**, 042303 (2023)





ALICE Col. QM2023



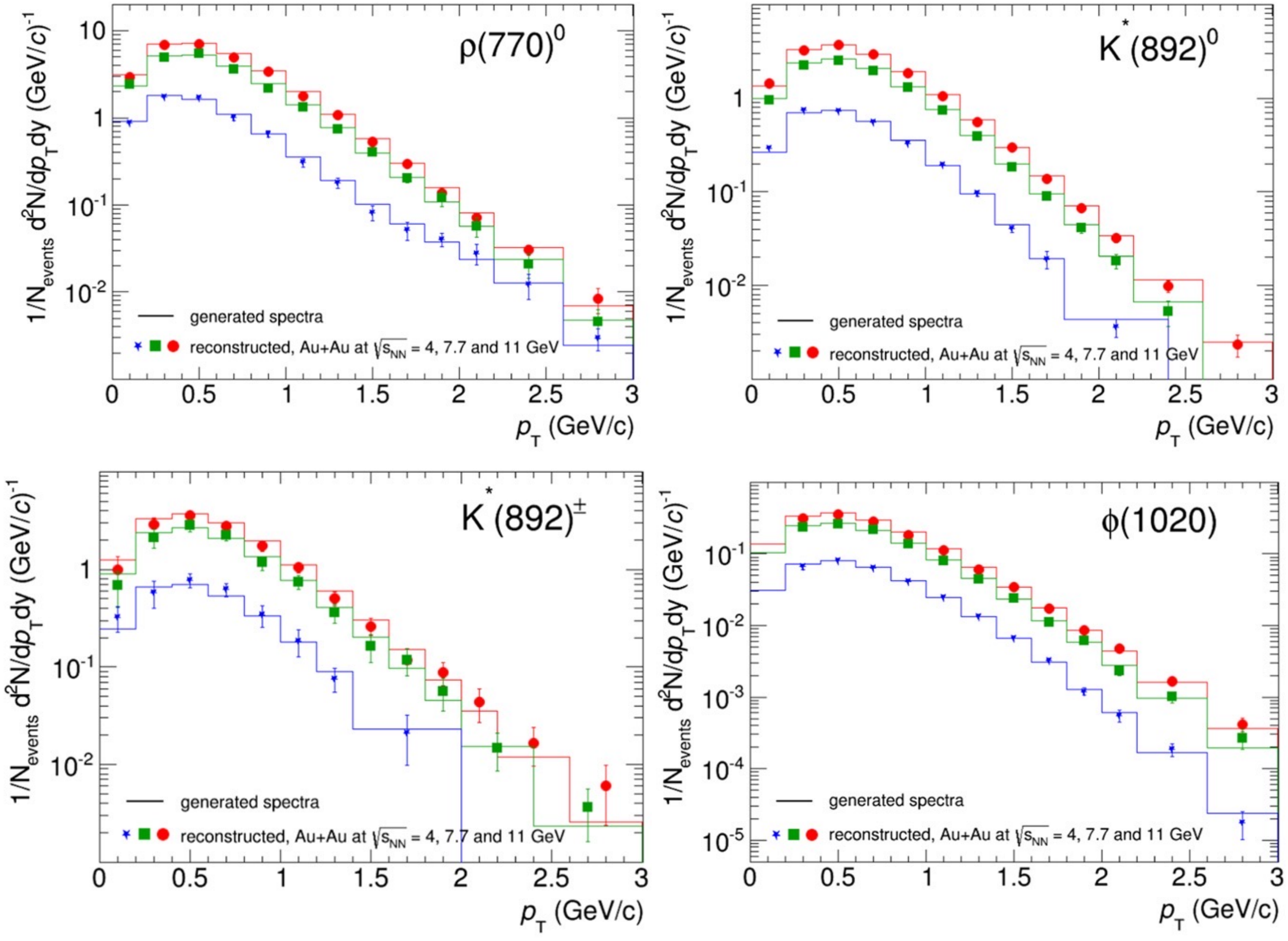
- Forward rapidity J/ψ ρ_{00}<1/3 at LHC
- Midrapidity J/ψ ρ_{00} ~ 1/3 at RHIC
- D^{*+} shows a clear p_T dependence

→ The underlying physics seems not converged?

Prospects at NICA-MPD for mesons

- The different species of vector meson spin alignment from RHIC/LHC seems not converged, independent measurements will be very helpful to understand the underlying physics

- NICA-MPD can identify the vector mesons well, thus will be excellent experiment to measure the light flavor spin alignment



Figs. from Zebo

Summary

- Spin polarization opens a new avenue to investigate heavy-ion collisions
- Global hyperon polarization is observed with the order of a few percent. It represents a measure of the average value of the global quark polarization in the system
- Global vector meson spin alignment is observed with a surprisingly large parttern for φ-meson. It represents a local fluctuation/correlation between quark and anti-quark polarization
- Measurements as a function of collision energies, different hadron species are on-going, rich physics to be explored, and the NICA-MPD will be very powerful to establish the feature of high-baryon density region